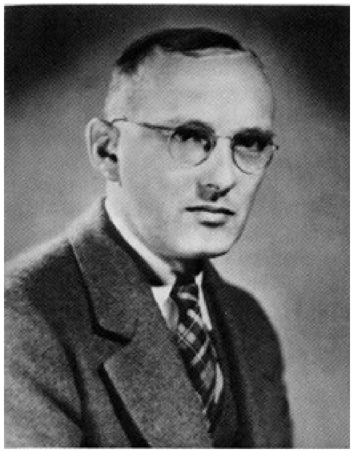
The Beast At The Center

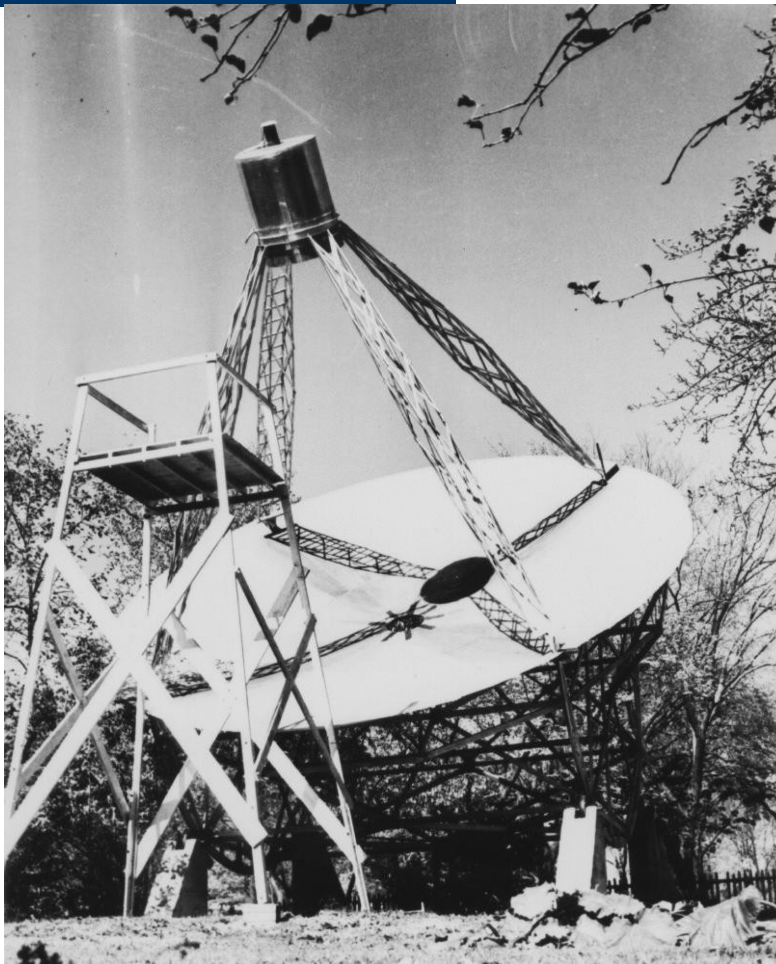
Karl Jansky (1905 – 1950)



- U of Wisconsin undergrad.
- Built a radio antenna on a rotating platform – *“Jansky's merry-go-round”*.
- In 1933 he discovered radio emission from the center of the Milky Way galaxy – he called it ***Sagittarius A*** object.
- He died at the age of 44 – probably, missing the Nobel Prize by only a few years.

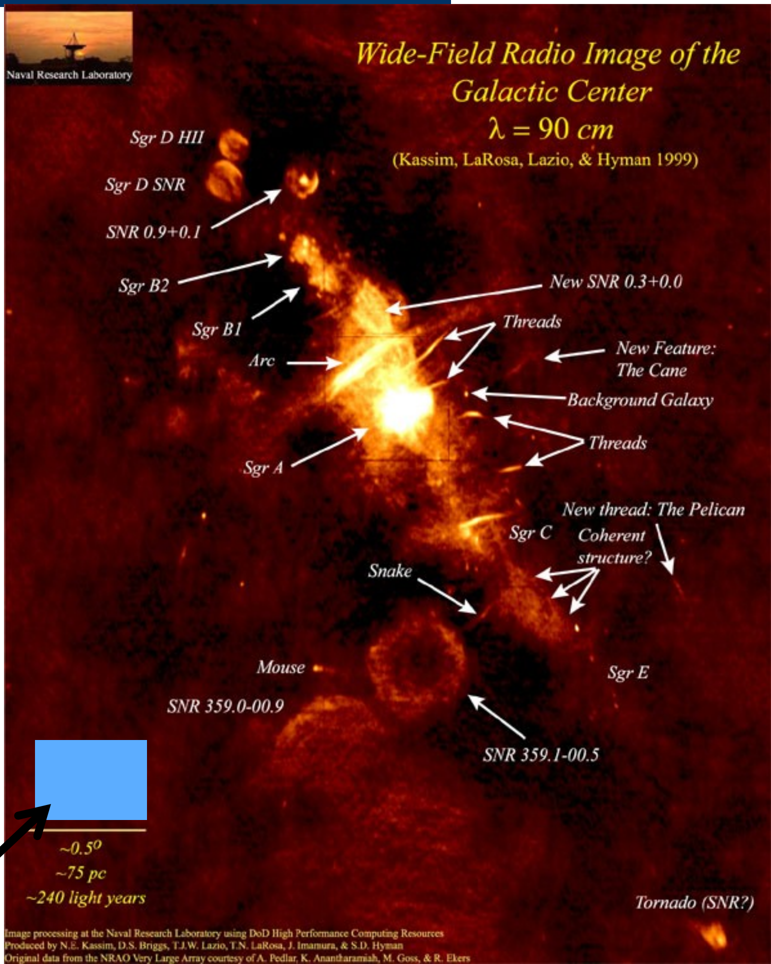
Reber Radio Telescope

- First radio telescope in the world – build by Grote Reber (1911 – 2002) in IL from Karl Jansky's blueprints.
- An astronomical unit of radio brightness – ***Jansky*** is named after Karl.



Center of the Milky Way in Radio

- Sagittarius A (***Sgr A***) object actually consists of 3 different things: an old hyper-nova remnant (Sgr A East), a cloud of gas (Sgr A West), and the true center of our Galaxy: ***Sagittarius A****.



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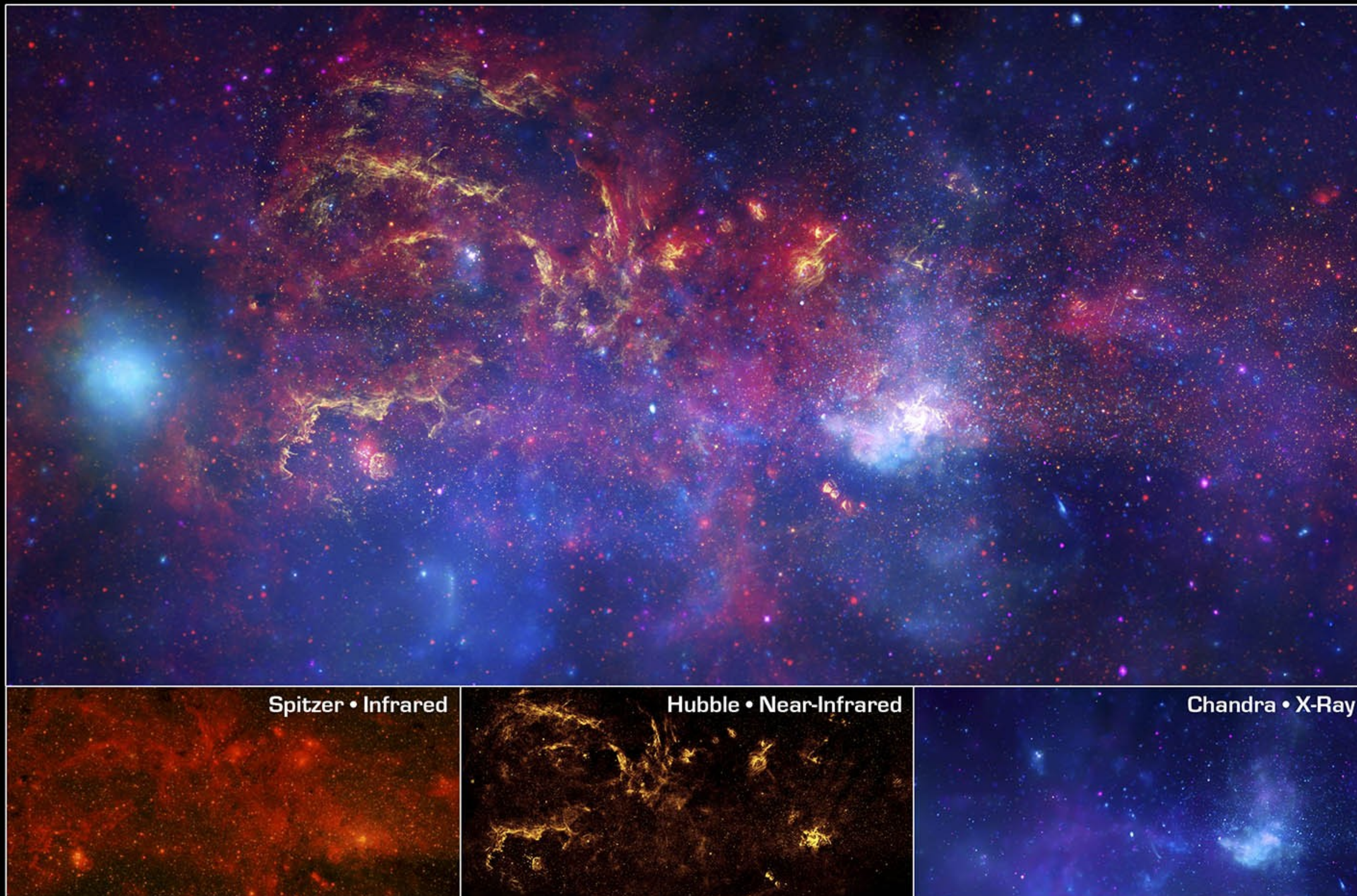

Great Observatories' Unique Views of the Milky Way

Spitzer Space Telescope • Hubble Space Telescope • Chandra X-Ray Observatory

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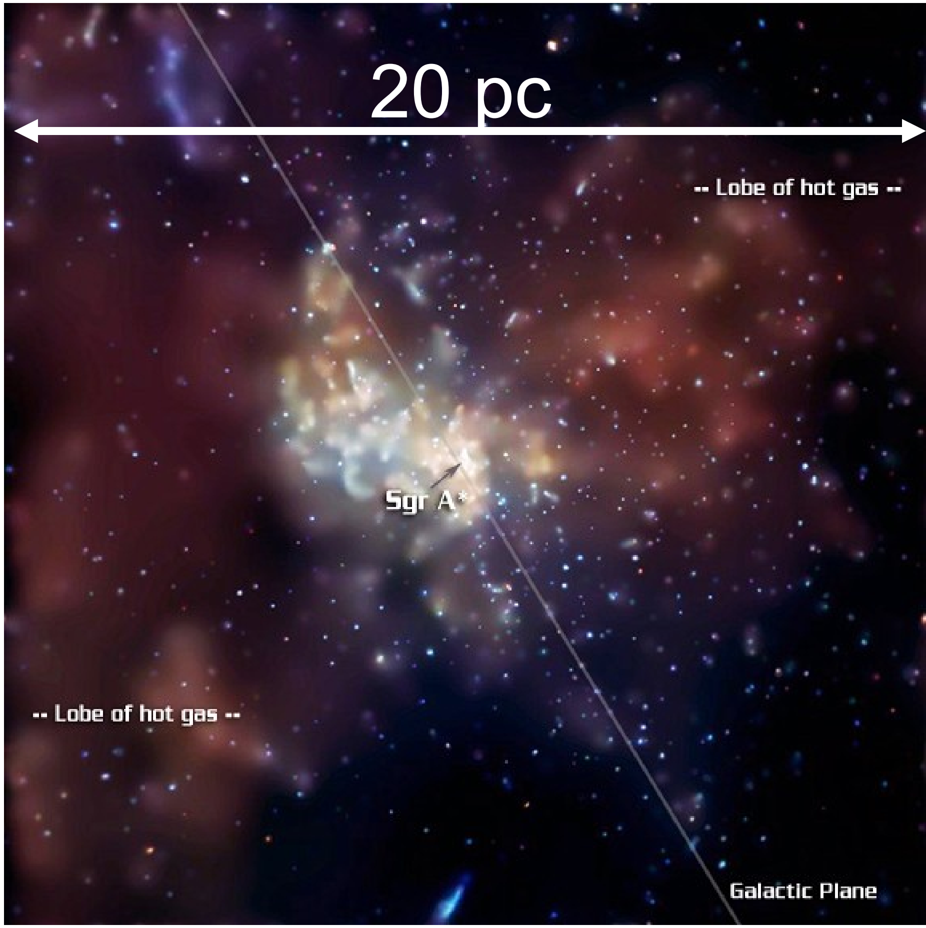
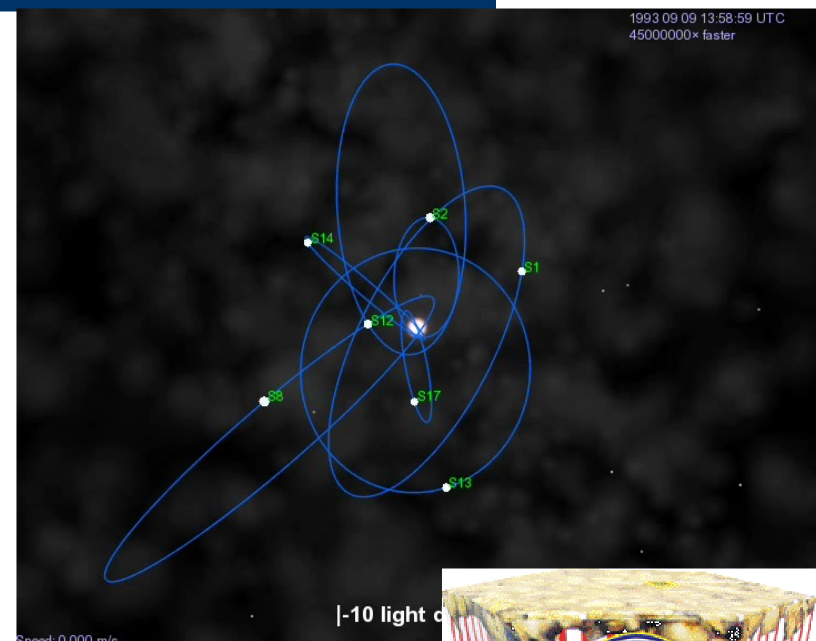
Center of the Milky Way in X-rays

- There is a lot of X-ray activity at the very center of the Milky Way.
- It appears as if Sgr A* is blowing hot gas away from the Galactic plane.



Stellar Orbits Around Sgr A*

- Since 1996, astronomers were tracking orbits of individual stars around Sgr A*.
- Stars move very fast near it – up to 5,000 km/s.



Question

- From the sizes and periods of stellar orbits around Sgr A*, we can determine:
  - **A**: masses of orbiting stars.
  - **B**: mass of Sgr A*.
  - **C**: mass of the Milky Way galaxy.
  - **D**: density of gas at the Milky Way center.
  - **E**: that astronomers have nothing better to do.

Mass of Sagittarius A*

- From stellar orbits, in particularly S2, we can measure the mass of Sgr A* - recall Kepler's third law:

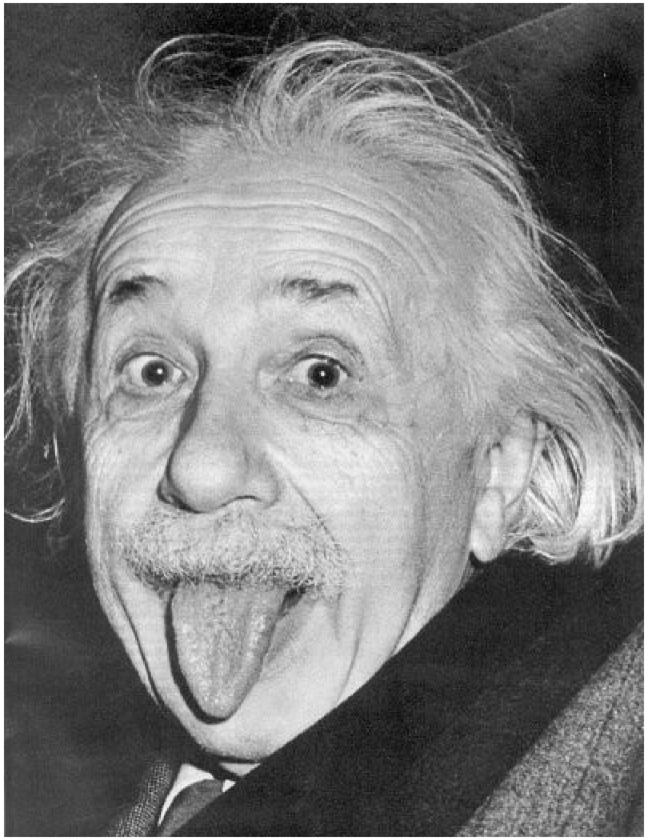
$$G(M_1 + M_2)P^2 = 4\pi^2 R^3$$

- Result: $M_{\mathrm{Sgr\ A^*}} = (3.3 \pm 0.7) \times 10^6\ M_\odot$ (3.3 million suns). Rather large for an object less than 0.37AU in radius!

- *Gas is blowing away*
- *In the mid of Milky Way.*
- *Stars whiz by like specs of light,*
- *Hurled by colossal might.*
- *What can take on such a role?*
- *Make a guess – it’s a black hole!*

Albert Einstein (1879 – 1955)

- Began his career as patent clerk in 1902.
- In 1905 developed Special Theory of Relativity.
- In 1908 became Assistant Professor at Bern.
- In 1915 developed General Theory of Relativity.
- In 1921 got Nobel Prize.



General Relativity

- Recall, that in Newtonian Mechanics there is this freak coincidence: the inertial mass is very close to the gravitational mass.

$$m_{\rm in} = m_{\rm gr}$$

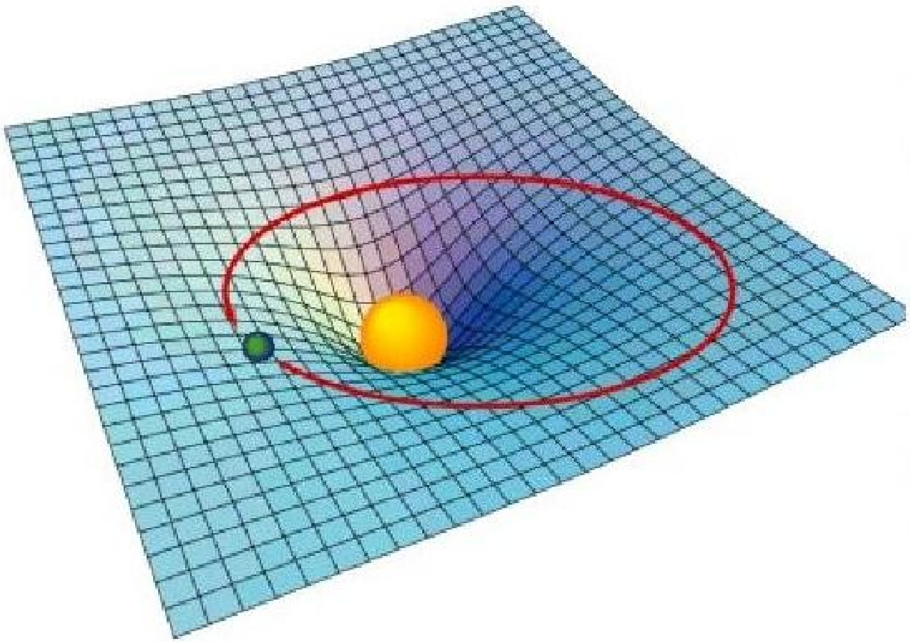
- Einstein resolved it in one shot: this is no coincidence, ***it is a law if nature!***
- There are no free lunches: he had to face the ramifications, and those were severe.

Relativity of Space and Time

- As the result, space and time lose their absolute being – they become ***relative***. We often talk about ***space-time*** as being one common arena for physical reality.
- Space also becomes ***curved*** (rather than being flat), and time becomes ***non-uniform*** (it flows at different rates in different places).
- In GR freely-falling objects try to move straight, but there are no straight lines anymore…

Curved Space

- Freely-falling objects are moving along ***geodesic lines*** – the straightest lines there are.



- Imagine space as a stretched rubber sheet.
- A mass on the surface will cause a deformation.
- Another mass dropped onto the sheet will roll toward that mass.

Einstein Equations: Physics

- Equations of GR relate the curvature of space-time (its ***geometry***), and its contents (***matter + energy***).
- Symbolically, they are

Geometry = Matter + Energy

- Which side is the cause?
  - **A**: geometry
  - **B**: matter + energy

Einstein Equations: Math

$$\frac{1}{2}g^{rs}\left(-\frac{\partial^2 g_{ij}}{\partial x^r \partial x^s}+\frac{\partial^2 g_{is}}{\partial x^r \partial x^j}+\frac{\partial^2 g_{rj}}{\partial x^i \partial x^s}-\frac{\partial^2 g_{rs}}{\partial x^i \partial x^j}\right)+\frac{1}{4}g^{qp}\left(-\frac{\partial g_{is}}{\partial x^p}+\frac{\partial g_{pi}}{\partial x^s}+\right.$$

$$\left.\frac{\partial g_{ps}}{\partial x^i}\right)\times\left(\frac{\partial g_{qj}}{\partial x^r}+\frac{\partial g_{qr}}{\partial x^j}-\frac{\partial g_{rj}}{\partial x^q}\right)-\frac{1}{4}g^{qp}\left(-\frac{\partial g_{ij}}{\partial x^p}+\frac{\partial g_{pi}}{\partial x^j}+\frac{\partial g_{pj}}{\partial x^i}\right)\left(\frac{\partial g_{qr}}{\partial x^s}+\right.$$

$$\left.\frac{\partial g_{qs}}{\partial x^r}-\frac{\partial g_{rs}}{\partial x^q}\right)-\frac{1}{4}g_{ij}g^{rs}g^{uv}\left(-\frac{\partial^2 g_{rs}}{\partial x^u \partial x^v}+\frac{\partial^2 g_{rv}}{\partial x^u \partial x^s}+\frac{\partial^2 g_{us}}{\partial x^r \partial x^v}-\frac{\partial^2 g_{uv}}{\partial x^r \partial x^s}\right)+$$

$$\frac{1}{8}g_{ij}g^{rs}g^{uv}g^{qp}\left(\frac{\partial g_{qr}}{\partial x^v}+\frac{\partial g_{qv}}{\partial x^r}-\frac{\partial g_{rv}}{\partial x^q}\right)\left(\frac{\partial g_{ps}}{\partial x^u}+\frac{\partial g_{pu}}{\partial x^s}-\frac{\partial g_{us}}{\partial x^p}\right)-$$

$$\frac{1}{8}g_{ij}g^{rs}g^{uv}g^{qp}\left(\frac{\partial g_{qr}}{\partial x^s}+\frac{\partial g_{qs}}{\partial x^r}-\frac{\partial g_{rs}}{\partial x^q}\right)\left(\frac{\partial g_{pu}}{\partial x^v}+\frac{\partial g_{pv}}{\partial x^u}-\frac{\partial g_{uv}}{\partial x^p}\right)=\frac{8\pi G}{c^4}T_{ij}.$$

Dynamical Space

- In GR space becomes a dynamical quantity. Space can be curved, perturbed, deformed in arbitrary way, and these deformations can change with time.
- Distortions of space can move – those are called ***gravitational waves***.
- Space can reconnect with itself – ***wormholes***.
- Space can flow into a point of infinite density – ***singularity*** – making a ***black hole***.

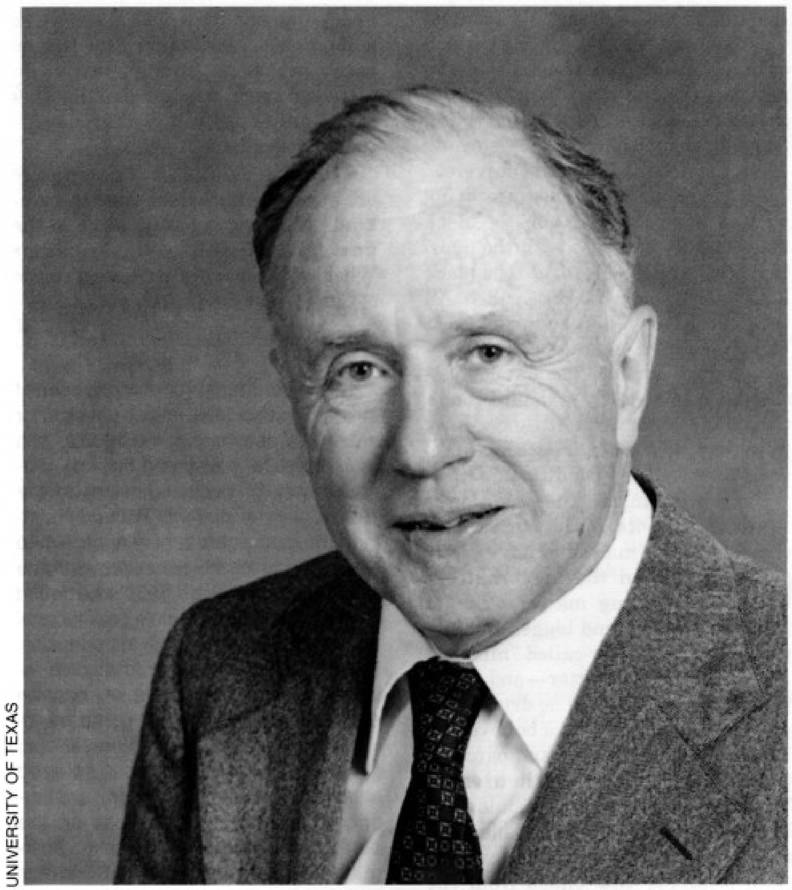
Black Holes

- Einstein published his paper on GR in Nov 1915.
- Karl Schwarzschild (1873-1916), German physicist turned soldier, found black holes mathematically in 1916.
- Schwarzschild died on the Russian front in May 1916 from disease.

We did not kill him!!!

Black Holes

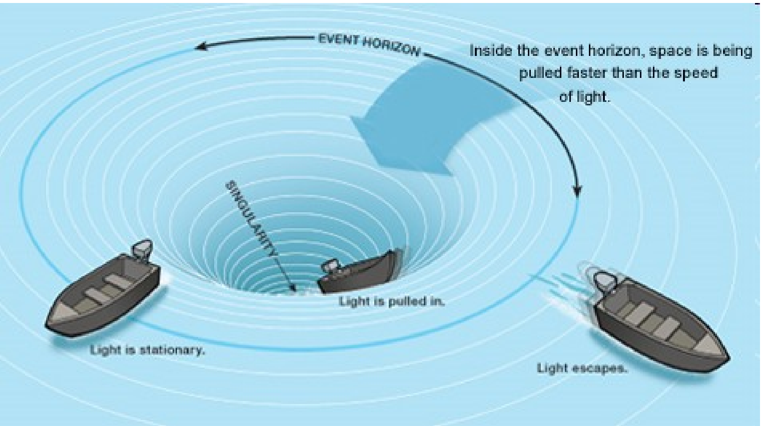
- The term itself coined by John Wheeler (1911 – 2008) in 1967.
- There are many ways to think about black holes. The best one is a “river of space” analogy.



Wheeler

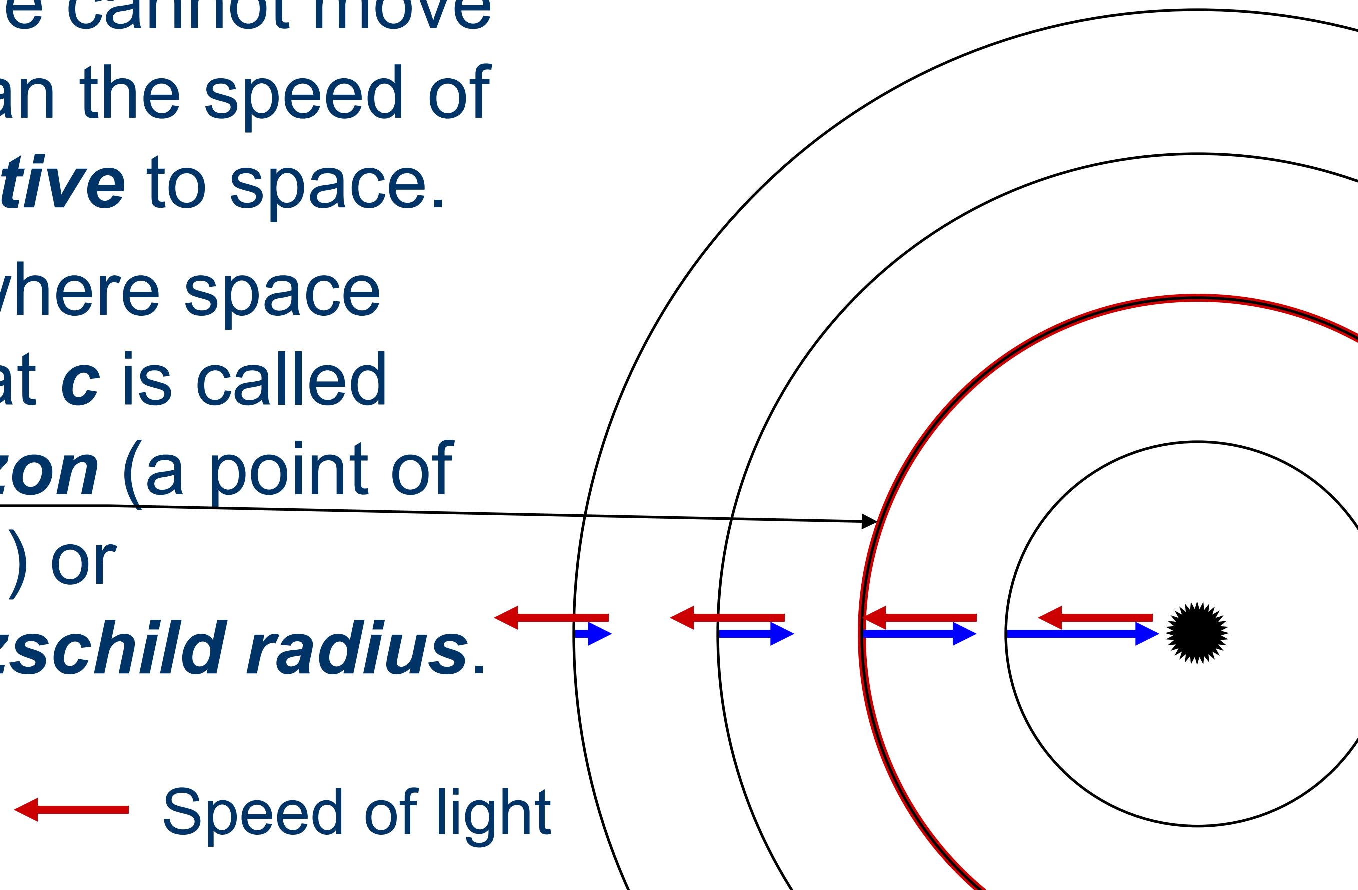
River Model of Black Holes

- Boat swimming against the river current can move around in slow places, but falls down the waterfall.



River Model of Black Holes

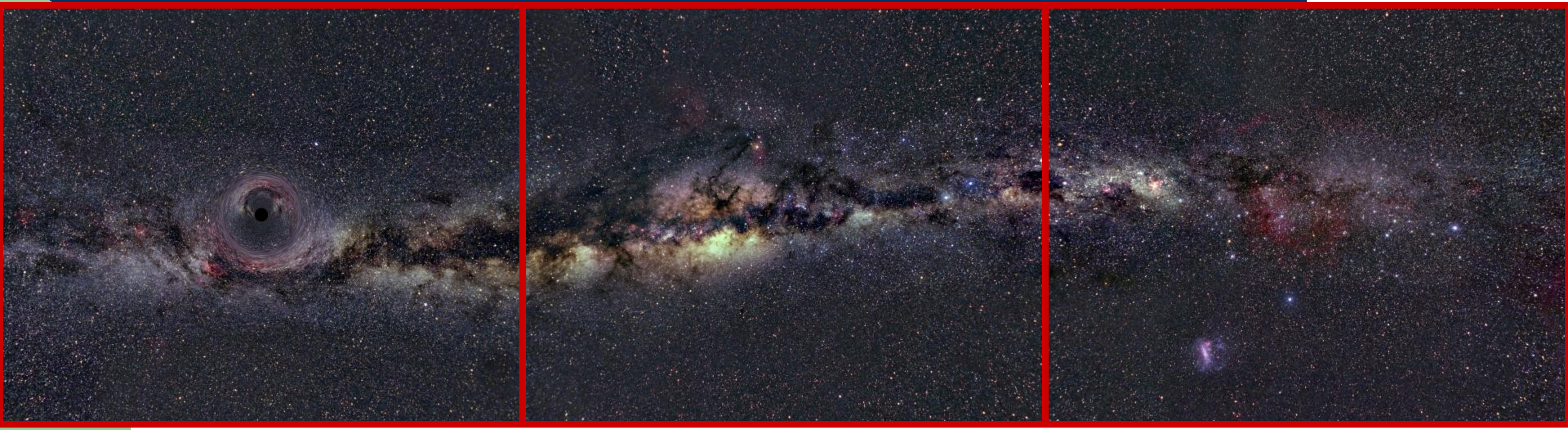
- In GR one cannot move faster than the speed of light ***relative*** to space.
- Radius where space flows in at ***c*** is called the ***horizon*** (a point of no return) or ***Schwarzschild radius***.

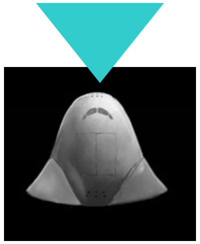


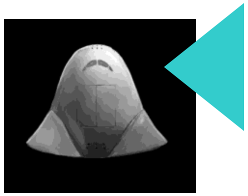
Flowing Space

- If the space flows into a black hole, wouldn't it all disappear eventually? ***No*** – there are no laws for the "conservation of space". Space can be destroyed and created.
- The universe expands because the space between galaxies expands – there is "more" space today than we had yesterday. That's ok – the mess in my kid's room does the same….

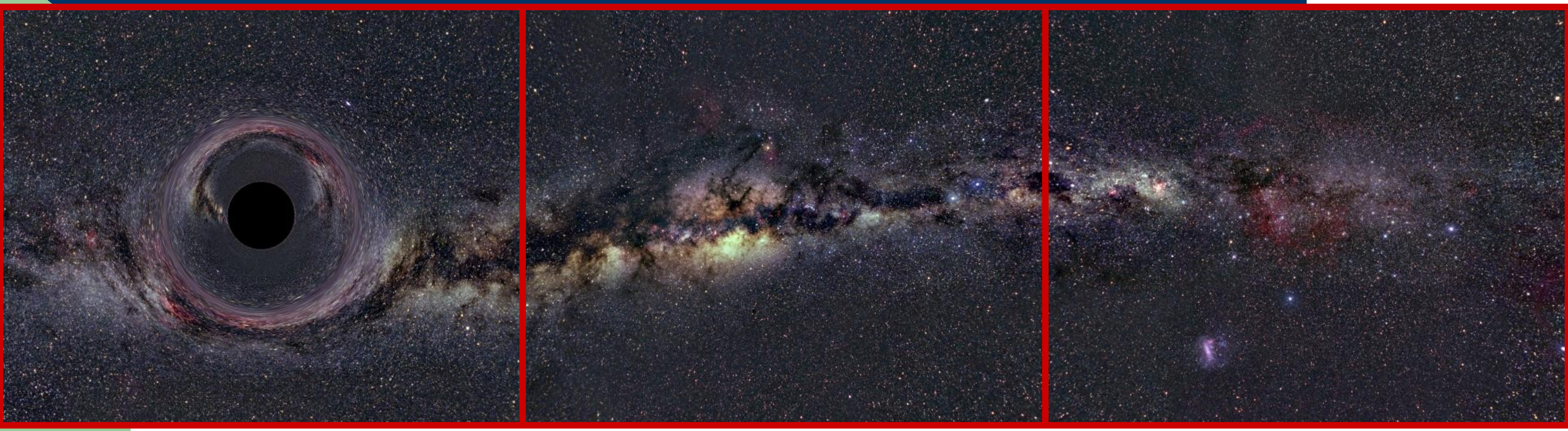
Falling into a Black Hole: 100 R_s

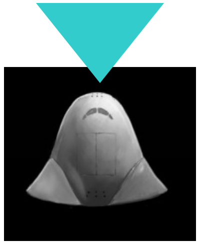


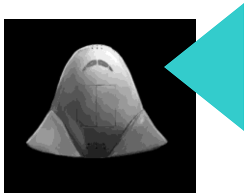




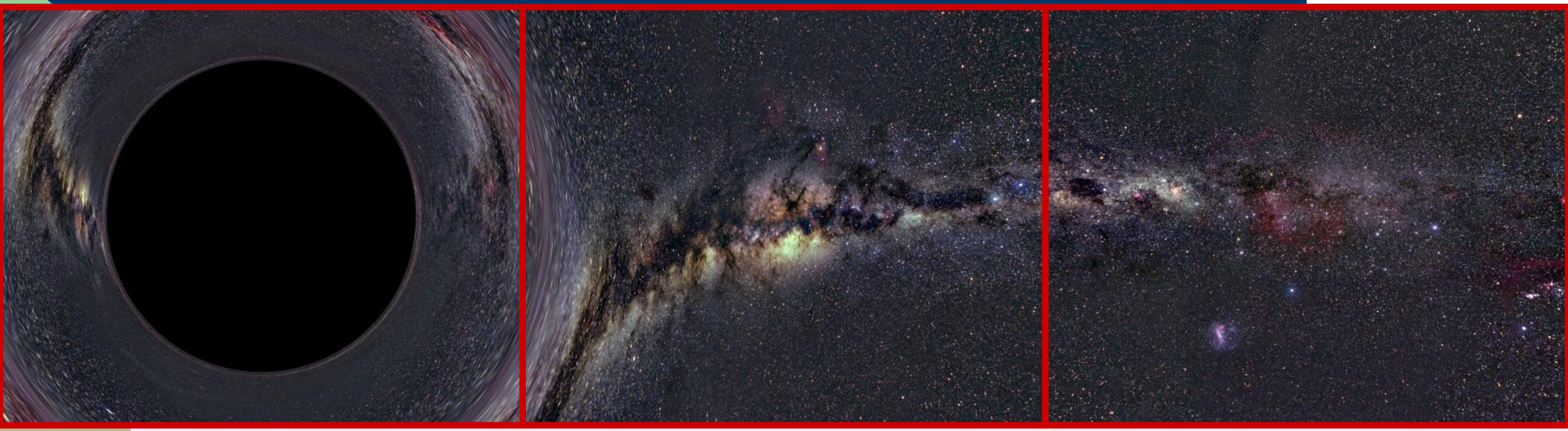
Falling into a Black Hole: 20 R_s

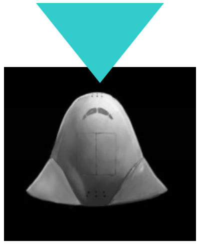


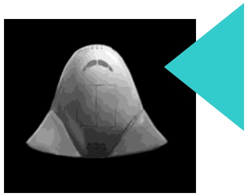




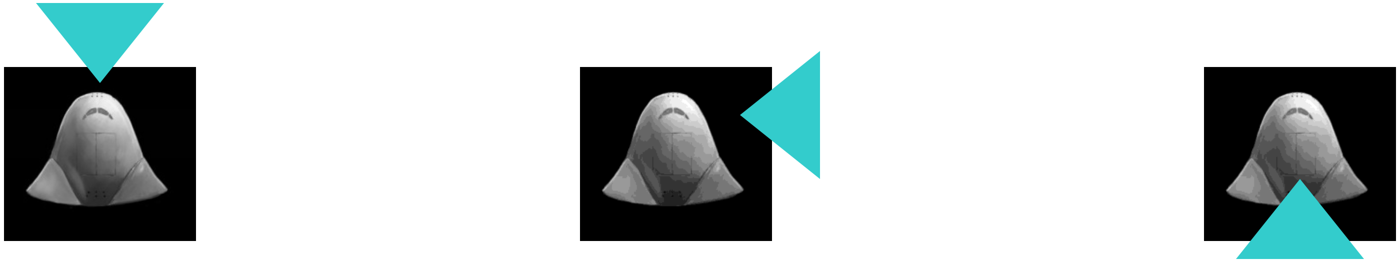
Falling into a Black Hole: 4.5 R_s



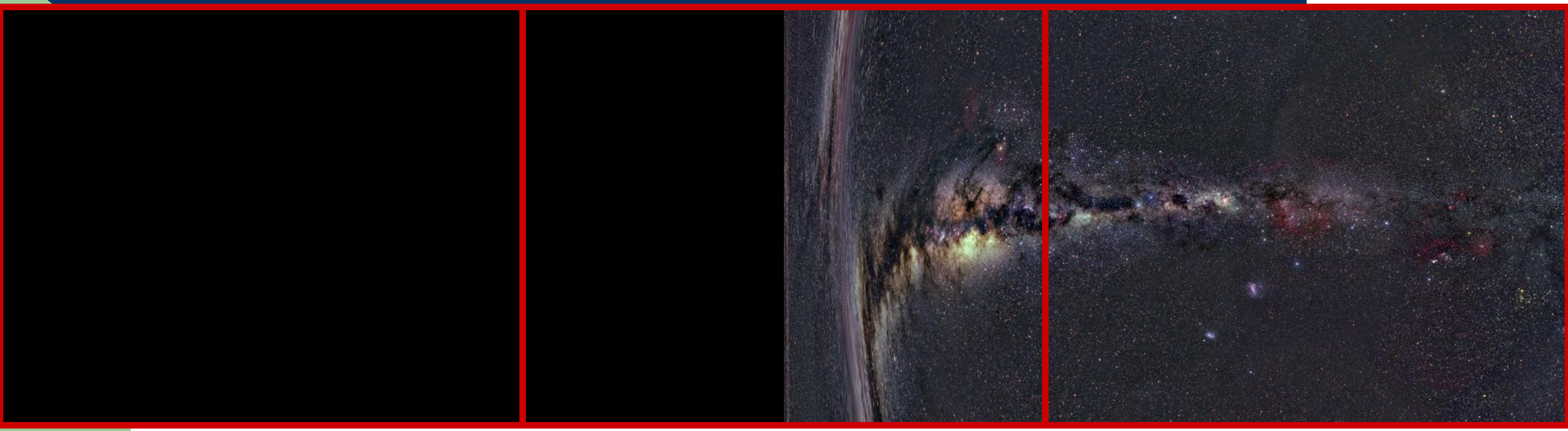


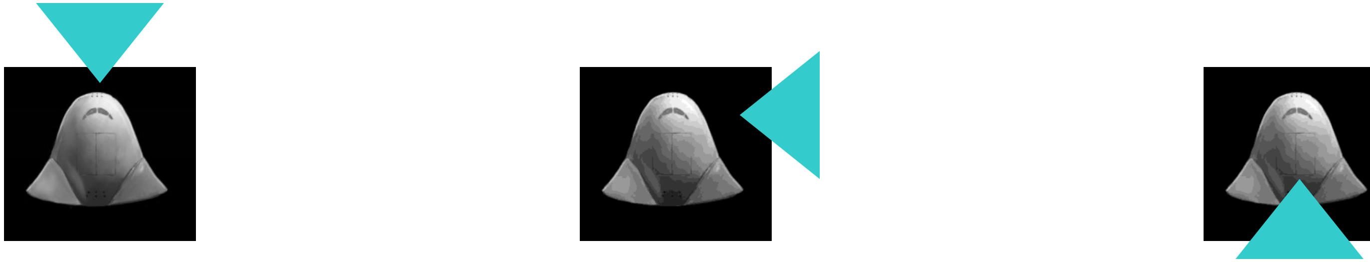


Falling into a Black Hole: 2.5 R_s

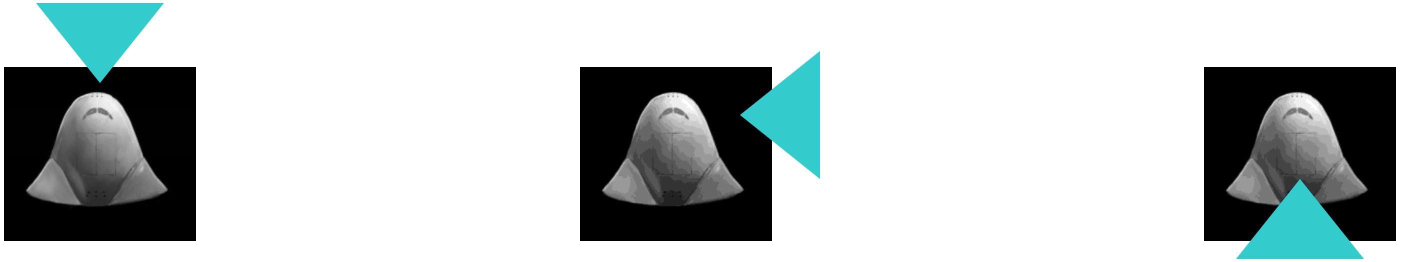


Falling into a Black Hole: 1.5 R_s

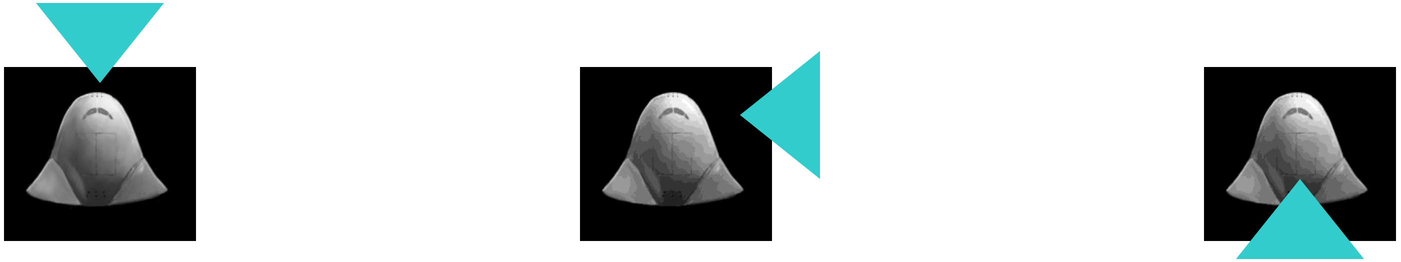




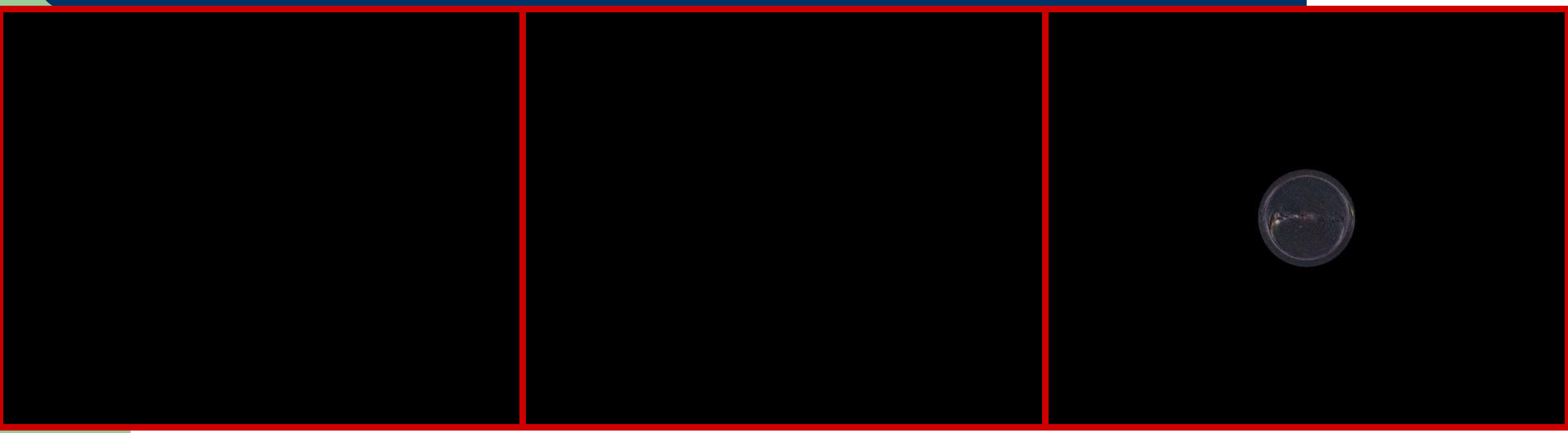
Falling into a Black Hole: 1.2 R_s

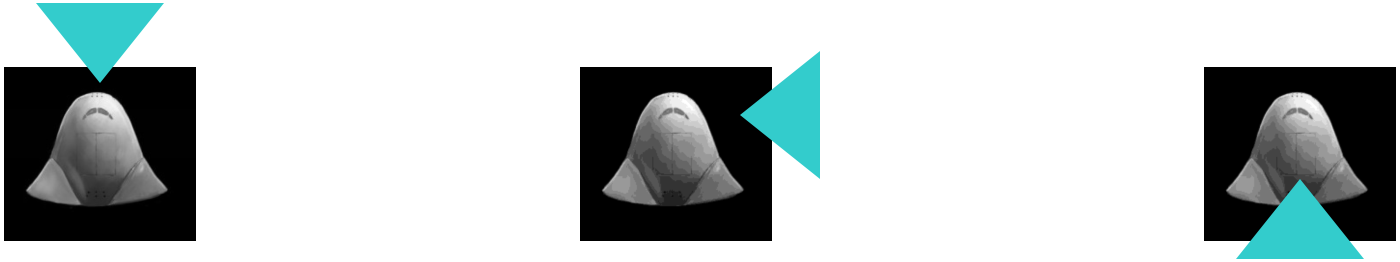


Falling into a Black Hole: 1.05 R_s



Falling into a Black Hole: 1.005 R_s





Sci-Fi Question

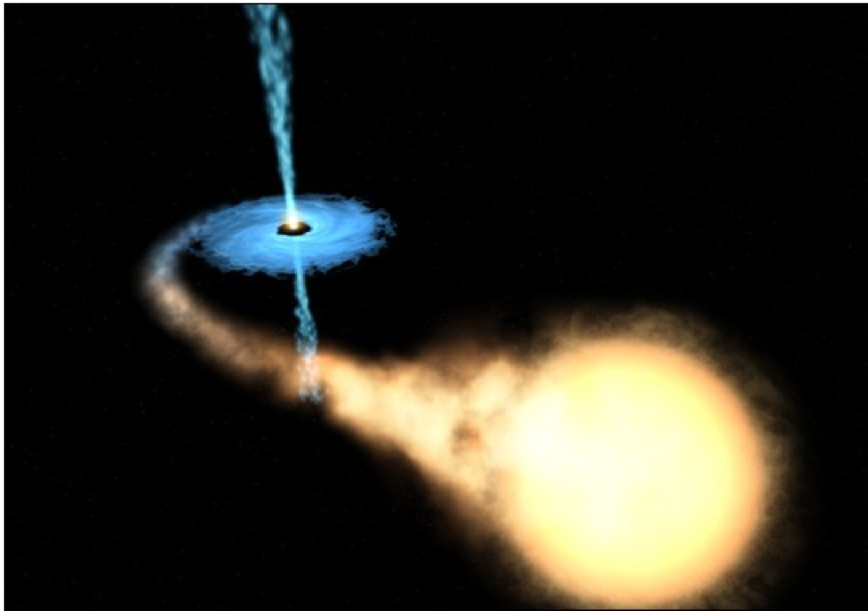
- Imagine that in 2511 a spaceship was orbiting a neutron star somewhere in the Galaxy. Suddenly, the neutron star started collapsing and quickly turned into a black hole. What would happen to a spaceship?
  - **A**: Nothing.
  - **B**: It will get sucked into a black hole.
  - **C**: It will lose balance and will fly away.
  - **D**: Tidal forces will crash it instantly.

Why Black Holes Are Not Black

- Recall, that very massive stars (above about 30 $M_\odot$) end up as black holes.
- Most of these stars form in binary systems. A companion is likely to be less massive – hence, it evolves slower.
- Many stellar mass black holes have Red Giant companions. Can you guess what happens?

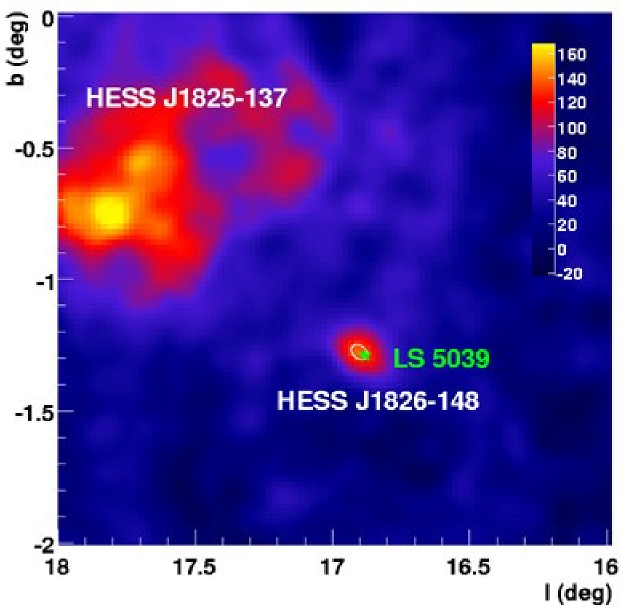
Accreting Black Holes

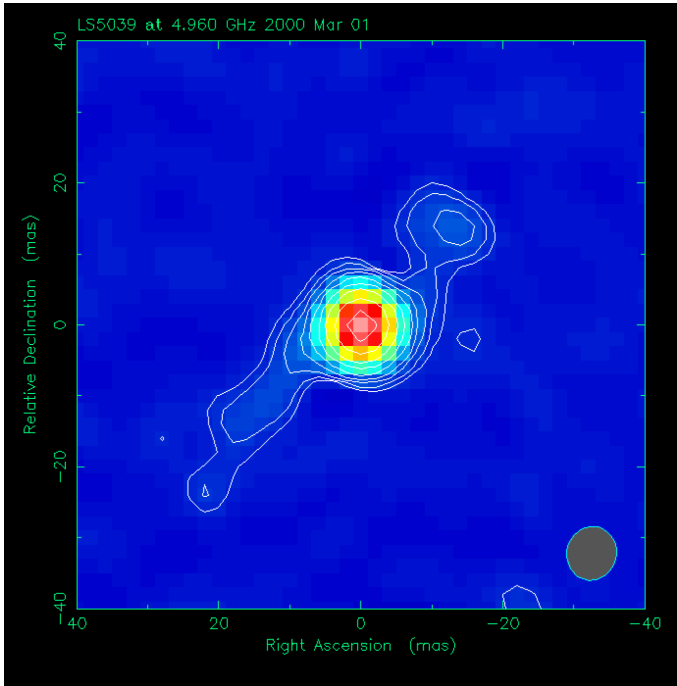
- A black hole in a binary system is likely to accrete gas from the companion. An accretion disk then forms.
- In the inner part of the disk the gas rotates close to the speed of light; friction heats it up to ~100 billion K.
- Would it remain dark?



“Microquasars”

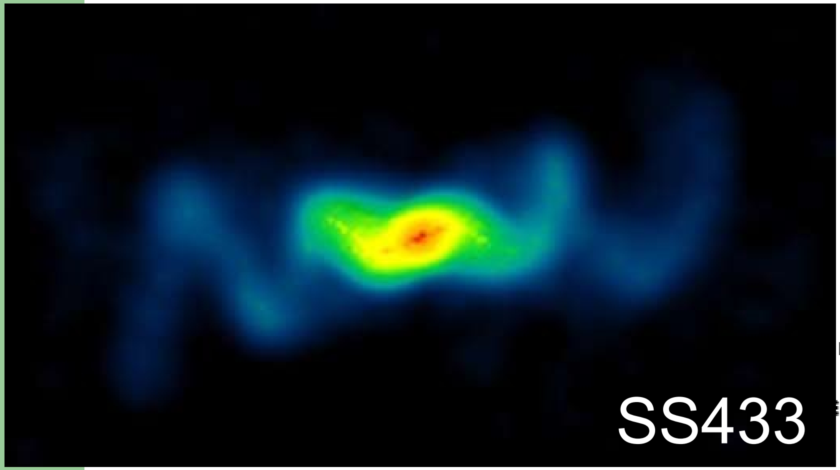
- Such black holes are called ***microquasars***. They are very bright in gamma-rays, X-rays, and also emit in radio.

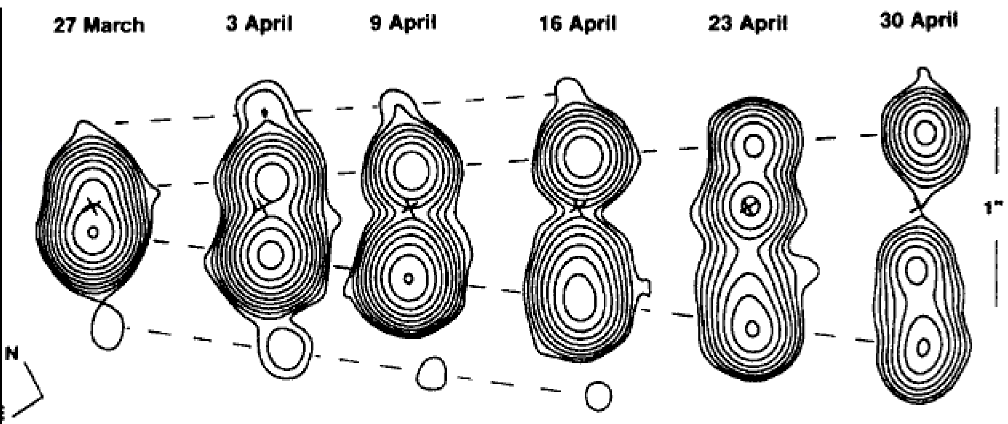




Microquasar Jets

- Many microquasars have jets. The most famous is dubbed SS433 – its jet precesses with a period of 160 days.





GRS 1915+105: 0.92 c